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SOLAR HOUSE SYSTEM INTERFACED WITH THE POWER UTILITY GRID,(U)
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(6) SOLAR HOUSE SYSTEM INTERFACED WITH THE POWER UTILITY GRID

(15) Contract N00014-71-C-0169

DDC FILE COPY

NR. 372-053
Date: 1975

(11) 1975

(12) 12p.

NOTE: Submitted 1/75 for Proc. Intl. Technical Meeting on Space, Rome, March 1975.

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SUMMARY

Photovoltaic cells may be used to convert sunlight directly into electrical energy and into low-grade heat to be used for large scale terrestrial solar energy conversion. Both forms of energy can be utilized if such cells are deployed in close proximity to the consumer (rooftop). CdS/Cu_2S solar cells are an example of cells which may be produced inexpensively enough to become economically attractive. Cell parameters relevant for combined solar conversion are presented. Critical issues, such as production yield, life expectancy, stability of performance, are discussed. Systems design parameters related to operating temperatures are analyzed. First results obtained on Solar One, the experimental solar house of the University of Delaware, are given. Economic aspects are discussed.

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This work was partially supported by a grant from NSF/RANN, by ONR and NASA and by a group of electric power utilities.

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1. INTRODUCTION

The energy needs of our society are steadily increasing due to the increase in population and the desire for higher standards of living (the Gross National Product is a monotonic function of the energy consumed[1]). The fuel supply is not sufficient to satisfy such needs in the future.

First natural gas, then oil, will be in short supply and will force consumers to explore alternative resources. It is cértain that current comfort conditioning with natural gas and oil must change to other forms of producing heat, such as using synthetic fuels, electricity using heat pumps, and solar energy. The latter has great attraction as non-depletable fuel; however, its intensity fluctuation and high first cost of the needed conversion equipment have prevented major use of solar energy.

With the increasing cost of conventional energy, a substantial change towards competitiveness is expected. This already has initiated some of the R & D programs in solar energy designed to solve technical and socio-economic problems and to make large-scale application feasible.

The economic restraint has caused reevaluation of several conversion concepts and has shown the need to consider not only energy but also entropy and other thermodynamic variables determining the "availability" of energy for the process in question. The following is a simple example for such a conversion system from which two forms of energy are obtained from solar radiation and used by the consumer without unnecessary (and uneconomic) entropy conversion.

The system uses photovoltaic cells which convert sunlight directly into electricity, and, while also heated by sunlight, provide low-grade thermal energy for comfort conditioning. When deployed in close proximity to the consumer (e.g. in solar panels on house roofs) such systems may supply a large fraction of the electrical energy and heat for most houses.

Solar cell arrays deployed in flat plate collectors may convert between 5% and 15% of solar energy into electricity and 50% to 60% into heat at moderate temperatures of 50°C to 80°C sufficient for water and space heating. This ratio is similar to the demand ratio in most houses.

Different kinds of photovoltaic cells are known; most developed are Silicon and CdS/Cu_2S cells.[2] Si-cells are highly efficient (up to 18%) and proven in many space and terrestrial applications, but they are expensive and cost reductions are limited. CdS/Cu_2S cells have been plagued by certain instabilities and lower efficiencies (up to 8%), but major improvements have been obtained recently, indicating feasibility to develop a very low-cost cell with high life expectancy and sufficient conversion efficiency to be economically attractive.

We will describe such a system containing CdS/Cu_2S solar cells as active element. This system has been incorporated in Solar One, an experimental solar house at the University of Delaware,[3] in operation since July 1973 (Fig. 1).

2. SOLAR ONE

This house uses 24 solar collectors (Fig. 2) of 1.20 X 2.40 m^2 each, mounted on a 45° south sloping roof. The collectors are double glazed (white glass inside, Lucite AR^R outside) and use air as heat transport fluid. A variety of fins are used to facilitate heat transfer from the collector plate to the air. The heated air is used to melt 3,200 kg of $Na_2SO_3 \cdot 5H_2O$ contained in a basement storage bin (capacity $\sim$ 250 kWh thermal) or to heat the rooms directly, or to be amplified by a heat pump in inclement weather.

During the summer the heat pump is used for air conditioning. It is then operated during night hours at off-peak utility power and the "coolness" is stored in 1150 kg of a $Na_2SO_4/NaCl/NH_4Cl$ eutectic[4] (capacity $\sim$ 50 kWh thermal) for daytime use. Cooling the condenser coil of the heat pump with cooler nighttime outside air also improves its coefficient of performance[5] (COP).

Three of the collector plates are covered with arrays of a total of 936 closely-spaced CdS/Cu_2S solar cells, a fraction of which are delivering (nominal) 120V to a lead acid battery (series of ten 12V, 80 Ah car batteries). A current controlled power supply is slaved to the solar panel output to provide make-up dc to simulate full coverage of all solar roof panels with solar cells.

2.1 PERFORMANCE OF THE THERMAL SUBSYSTEM

A variety of solar panels tested was distinguished by different optically absorbing surfaces* and different finning of the air duct. Conversion efficiencies from 30% to 75% were observed at maximum collector plate temperatures of 35°C above outside temperatures and at 800 W/m^2 insolation. The temperature difference of the collector plate to the heated air of the best collectors is approximately 4°C (Fig. 3) with heat transfer coefficients up to 330 Joules/m^{2}sec°C being observed.[6]

The maximum collector plate temperature is limited by efficiency reduction and life degradation of the CdS/Cu_2S solar cells. With current cells, this limit is estimated** to be 65°C.

In order to melt the heat storage salt (T_m=49°C), two clear days (12 h) are needed (ΔT=12°C, 25 kW transfer at 1.5 m^3/s flow rate and 190 m^2 salt container surface in the bin). The salt melts congruently. It needs a nucleation device to avoid major supercooling in the cool-down cycle. Such devices were developed by Dr. M. Telkes and work satisfactorily in the Solar One storage bin. Theoretical heat recovery and no degradation of performance are observed.

The coolness storage bin can be charged within 10 hours from the heat pump (ΔT=5°C, 2.5 kW transfer at 0.5 m^3/s flow rate and 120 m^2 container surface). Its stored energy is sufficient to cool the house during most of the day, even during severe summer weather. Within the experimental error, the theoretical amount of heat is recovered, however, over a temperature range of $\pm$5°C from the melting point of the original salt eutectic, indicating some changes during cycling but no major deterioration of the cooling effect of the bin.

Despite substantial experimentation, causing frequent shut-down during the heating season of 1973/74, the house has been supplied with 60% of its heating needs by solar energy.

During part+ of the first heating season, the heat pump has operated alternatively to a resistance heater (the latter used at outside temperatures below 4°C) with an overall++ COP of 1.7. The overall COP of the cooling-storage cycle (including losses and perioidic defrosting of the evaporator coil during charging) is 1.5. Major improvements are expected for the next heating season by extensive use of heat storage (not used during the heating season 1973/74) and a tandem operation of heat pump and resistance heater.

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* selective and non-selective black

**Doping of the CdS may increase this limit, possibly close to 100°C (see Ref. 7).

+ Up to January 8. For comparison, during the second part of the heating season, only the resistance heater was used.

++ including the energy used for resistance heating

Improvements of the cooling COP are expected by pump adjustments for summer operation to avoid icing and by better insulation to reduce thermal losses from the bin cycle.

2.2 PERFORMANCE OF THE ELECTRICAL SUBSYSTEM

The CdS/Cu_2S solar cell arrays are arranged in 8 X 13 cell segments, separately encapsulated within a 77.5 X 115 cm^2 frame between a galvanized steel substrate and a 0.63 cm thick Plexiglas cover. The inner cavity is continuously flushed with high purity nitrogen to prevent more rapid degradation in humid air.

Each array is loaded with a 75 Ohm resistor and is always kept at temperatures below 65°C via heat exchange through fins at the panel back to the air duct in the solar roof collectors. During the summer, chimney-action is sufficient to achieve this temperature limitation during most of the time. Only during an average of 1.5 hr/day, a 2 HP fan is used (intermittent duty cycle) for forced air cooling.

Simulation for complete coverage of all 24 collectors with currently deployed best subpanel arrays results in about 12 kWh/clear day (May 1) electric energy harvesting at an overall systems conversion efficiency of almost 3%. The array was assembled from cells of approximately 4% efficiency. The loss of conversion efficiency of the array compared to the single cells is caused by some cell mismatch, losses through two sheets of Plexiglas (15%) and elevated temperature operation (voltage reduction 0.3% per degree C).

The output of the solar arrays is monitored continuously. During "clear" days at noon a current-voltage characteristic is taken and the actual conversion efficiency is obtained by dividing the power at the maximum power point by the insolation measured simultaneously with a pyranometer. The actual values as observed are plotted in Figure 4; they scatter for reasons of different spectral sensitivity of solar cells and pyranometer and some differences in temperature. A systematic seasonal variation can be related to changes in the angle of incident. With the experimental error, no degradation is observed.

The results reported so far seem to indicate technical feasibility of using CdS/Cu_2S solar cells for partial electrification and heating of houses. The question of economic feasibility will be addressed in the following section.

3. ECONOMIC ANALYSIS

Measurable economic factors are divided into:

a) first cost of the solar system;
b) systems or components life expectancy;
c) annual cost;
d) annual average of harvested energy;
e) stand-by equipment required.

Other factors--such as appeal of solar energy, constant annual value of amortization vs. uncertain cost acceleration of conventional energy and "retirement security" after the system is amortized (free energy after amortization), as well as possible government assistance such as reduced taxation (already law in Arizona and Indiana), loans at reduced interest rates, and building code requirements (currently discussed in Florida)--may help to promote widespread use, but are not part of this report.

3.1 FIRST COST

Most critical for market initiation is the reduction of first cost to acceptable levels. The limited availability of capital is a severe restraint

and can best be visualized on a per capita basis. House and car are the most expensive items of necessity to the average affluent family. A solar house conversion system currently estimated between $4,000 and $10,000 will rank between these two investments and this will present a major barrier for widespread use. The need for cost reduction and for increased benefit (addition of electric conversion) is obvious.

Solar heating equipment is material intensive; hence, cost reduction is limited. Photovoltaic cells are high technology devices. Here cost reduction could provide the key for major acceptance of a solar house conversion system.

Major factors determining the cost of solar cells are: estimated material cost, 40%; amortization of production equipment, 30%; direct labor, 5%; overhead, 20%; and cost of energy, 5%--for a total factory selling price* of approximately $15 per m^2 at a production yield of 80% and a profit after taxes of 15%.

With an efficiency of 8% (maximum currently documented = 8.3%), the above price converts to $\sim$\$200/peak kW.

One way to analyze the economics of the combined system is to add the photovoltaic cells instead of the black solar panel coating to a conventional solar heating system for upgrading such system and to obtain electric energy in addition to heat. With an estimated conventional collector price[9] between $40 and $100/$m^2$, the modification results in a minor change of price.

Similarly, the addition of electric power processing equipment (wiring, switching, protection, minor storage and partial inversion) with an estimated price of $500 to $1,500 per house** adds only a minor fraction to the price of the conventional solar heat processing and storage system. However, the benefit obtained through this addition is substantial, as indicated in Section 3.4.

3.2 LIFE EXPECTANCY

Currently the storage subsystem seems to have the shortest life. Critical is the electrical storage with five years expectation for lead acid batteries.

The heat pump may have similar limitation, although substantial improvements seem possible.

The CdS/Cu_2S solar cell deserves major attention. The degradation uncertainties are not yet understood; however, photochemical reactions involving humid oxygen and copper diffusion into CdS are two processes believed to contribute to the degradation. The first seems to be reversible (treatment in H_2 causes cells degraded in humid air to recover at least partially).[10] The latter causes substantial changes near the heterojunction and influences space charge and potential distribution, causing degradation of the cell output. It seems possible to reduce such degradation and consequently increase the life expectancy by proper doping[7], counteracting the effect of copper diffusion. Neglecting such doping, diffusion data indicate life expectancies in excess of 15 years[11] under "controlled rooftop conditions+." Accelerated life tests at elevated temperatures have shown a range of life expectancies, indicating that improvement can be expected. Highest life expectation extrapolated++ from accelerated tests measured at 56°C in nitrogen is approximately 100 years.

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* Estimated for a production rate in excess of 3 Million m^2 per year.
**single family unit
\+ an average of 5 hrs/day at 50°C
\+\+ Caution is necessary as the extrapolation does not anticipate possible additional effects which may become dominant later.

3.3 ANNUAL COST ESTIMATES

The annual cost of the solar system is composed of:

a) the amortization of the system over the length of the loan to pay for the first cost;

b) the interest of the loan [usually combined with a) to a fixed monthly rate];

c) maintenance;

d) interims replacement;

e) fraction of property, taxes relating to increased house value;

f) insurance;

g) servicing charges, or charges to interconnect with conventional system.

Charges a) and b) currently add up to 12% for a system of approximately 15 years life. Reevaluation is necessary with developing mortgage markets.

Solar systems must be developed to a degree that they are essentially maintenance-free. A contingency is assumed at 0.5%.

Interims replacement is necessary for batteries (improvements require a technological breakthrough). This, plus bearings, compressor and other parts, may add up to a yearly rate of 1%.

Property tax apportioned to the solar system is probably quite different from district to district. An acceptable average may be 0.5%.

Insurance may be initially high and come down as confidence increases. An approximation of 0.5% is suggested.

The most involved component is charge g), with need for explanation. Desire for reliability of any energy system indicates the need to interconnect with a conventional system, such as the oil (or gas) heating system and the electric power utility. This makes both groups ideal candidates to service the entire system and supply make-up energy*, when the solar component is insufficient. A combination contract for servicing and conventional energy (fuel) delivery with performance guarantee is envisaged. First cost subsidies may be possible when a better return on investment justifies such path. Supply and demand profiles will influence the business plan. It is difficult to provide general guidelines. Five percent may give sufficient incentives with a 25% subsidy of first cost.

The total fraction of the first cost for cases a)-f) is 14.5%, or for cases a)-g) it is 19.5% (of 75% of the first cost); i.e. both cases are selected so that the annual costs are substantially the same, but for certain investors and for the other involved parties, the second case may be preferred. The ratios in g) may be modified according to local incentive distributions.

3.4 ANNUAL AVERAGE OF HARVESTED ENERGIES (COST OF SOLAR ENERGY)

The amount of harvested energy depends on system size and on climate. Only part of this energy is utilized for economical storage/collector size relation for reasons of storage overflow at times of low consumption. Extensive computer calculations are performed[12,13] to estimate optimization.

*Such make-up energy is always necessary in an economical system since otherwise excessive storage capacity is required.

For the purpose of this paper, it may suffice to give as example for Delaware climate a 75 m^2 collector with a conversion system similar to the one in Solar One. Using heat only for space heating during the winter and for water heating, a total of 30,000 kWh thermal may be utilized for a single family dwelling from such collectors. With 6% overall conversion efficiency of the photovoltaic panel, a total of 8,000 kWh electrical energy could be supplied and used*. With a reasonable consumer cost ratio of 1:3,5 thermal to electrical kWh, an equivalent of 16,000 kWh(el) is used.

Assuming that with large scale production, such system could be installed for $5,000 (with credit for conventional components not used in such a solar house[8]), one obtains with 19.5% annual cost $725/year, or 4.5¢/kWh(el) (or $1.30 per Million "Btu").

These figures compare only in certain parts of the USA favorably with current costs. Future cost ratios (energy to other commodities) may not change dramatically for some time to come (before certain key fuels become substantially less available). Hence it is expected that solar energy conversion will find substantially different initial market potential in different regions of the USA.

However, the estimates suggest that with mass production, techno-economic feasibility exists, and it is indicated that with high-technology penetration such as the CdS/Cu_2S photovoltaic conversion, the total conversion system could become sufficiently attractive to permit a substantially accelerated market penetration into the new building market.

3.5 STAND-BY EQUIPMENT

We recognize that for reliability reasons, stand-by equipment is necessary. For electricity this means additional conventional equipment, presenting increased difficulties in the tight money market. Without interconnecting different units, an addition of at least 0.85 kW per family unit in stand-by power is necessary. With individual storage and some means to interconnect** to increase diversity, a substantial reduction of this stand-by power seems feasible.

On the other hand, solar installations do not aggrevate peak demand in regions in which a positive correlation between peak height and insolation is observed, provided that the total power demand of the solar installations is kept below the fraction of correlation. This can be as high as 10% of the total maximum demand in regions at which a large fraction of the peak demand is carried by air conditioning loads.

4. ACKNOWLEDGEMENT

It is a great pleasure to acknowledge the contribution of a large group of scientists and engineers of the Institute of Energy Conversion to the work and results reported here, and it is difficult to single out a few. However, a special note of gratitude is due to Drs. M. Telkes, T. M. Kuzay, M. A. S. Malik, D. B. Miller and H. M. Windawi, who were involved to a major degree in Solar One or in the results reported here.

* no waste assumed

**For instance, by cluster disconnect from the final transformer while the insolation is large and using the lines between the different houses for dc interconnection and battery charge and demand averaging.

REFERENCES

1) G. C. Szego, ITS-report C 645 to NSF/RANN: "The U.S. Energy Problem" (1971).
2) M. Wolf et al, Final NASA report NASW-1427, June 1968.
3) K. W. Böer, "The Solar House and Its Portent," Chem.Tech. 3, 394 (1973).
4) M. Telkes, "Storage and Solar Heating/Cooling," ASHRAE Transactions (1974), in print.
5) S. I. Freedman and J. C. Dudley, American Chemical Society, 7th IECEC Proceedings (1972), p. 1256.
6) T. M. Kuzay, M.A.S. Malik, S. M. Ridenour and K. W. Böer, "Solar One: First Results," Part 2, ISES Meeting, Ft. Collins, August 1974.
7) W. Palz et al, Proceedings of the 8th Photovoltaic Specialists Conference, IEEE (1970).
8) K. W. Böer, J.Environm.Sci., Jan/Feb. 1974, p. 8.
9) Phase Zero Studies of G.E., TRW and Westinghouse, NSF/RANN, 1974. Final Reports NSF/RANN-74-021A, 022A, 023A.
10) Semiannual Progress Report NSF/RANN/SE/GI-34872/PR74/2, University of Delaware, Institute of Energy Conversion (1974).
11) K. W. Böer et al, Technical Report NSF/RANN/SE/GI-34872/TR74/1 (1974).
12) G.O.G. Löf and R. A. Tybout, Solar Energy 14, 253 (1973) and 16, 9 (1974).
13) L. W. Butz, W. A. Beckman and J. A. Duffie, "Simulation of Solar Heating and Cooling," paper submitted to Solar Energy (1974).
14) A. D. Little, Inc., Report on Solar Climate Control Project (1974).

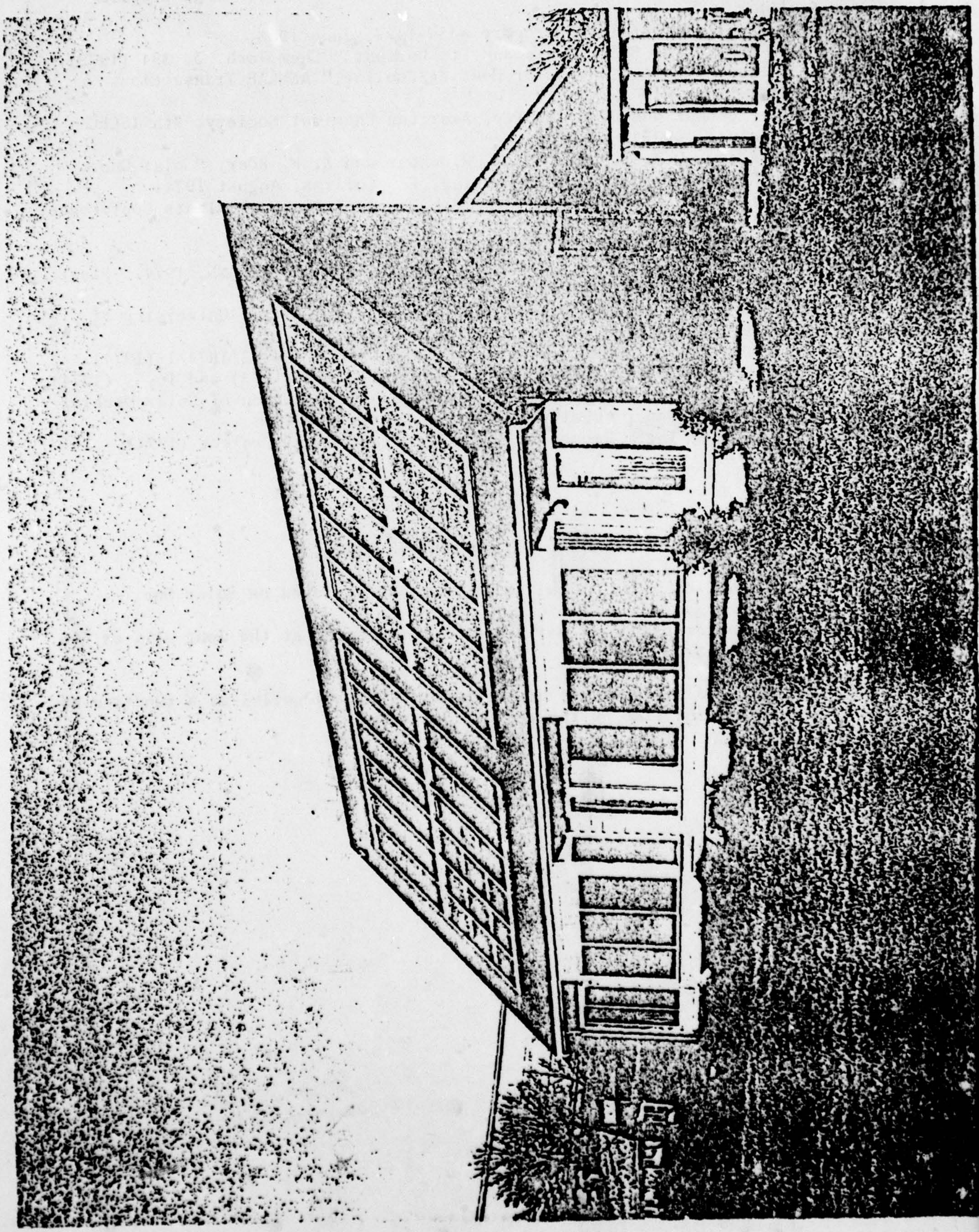
FIGURE CAPTIONS

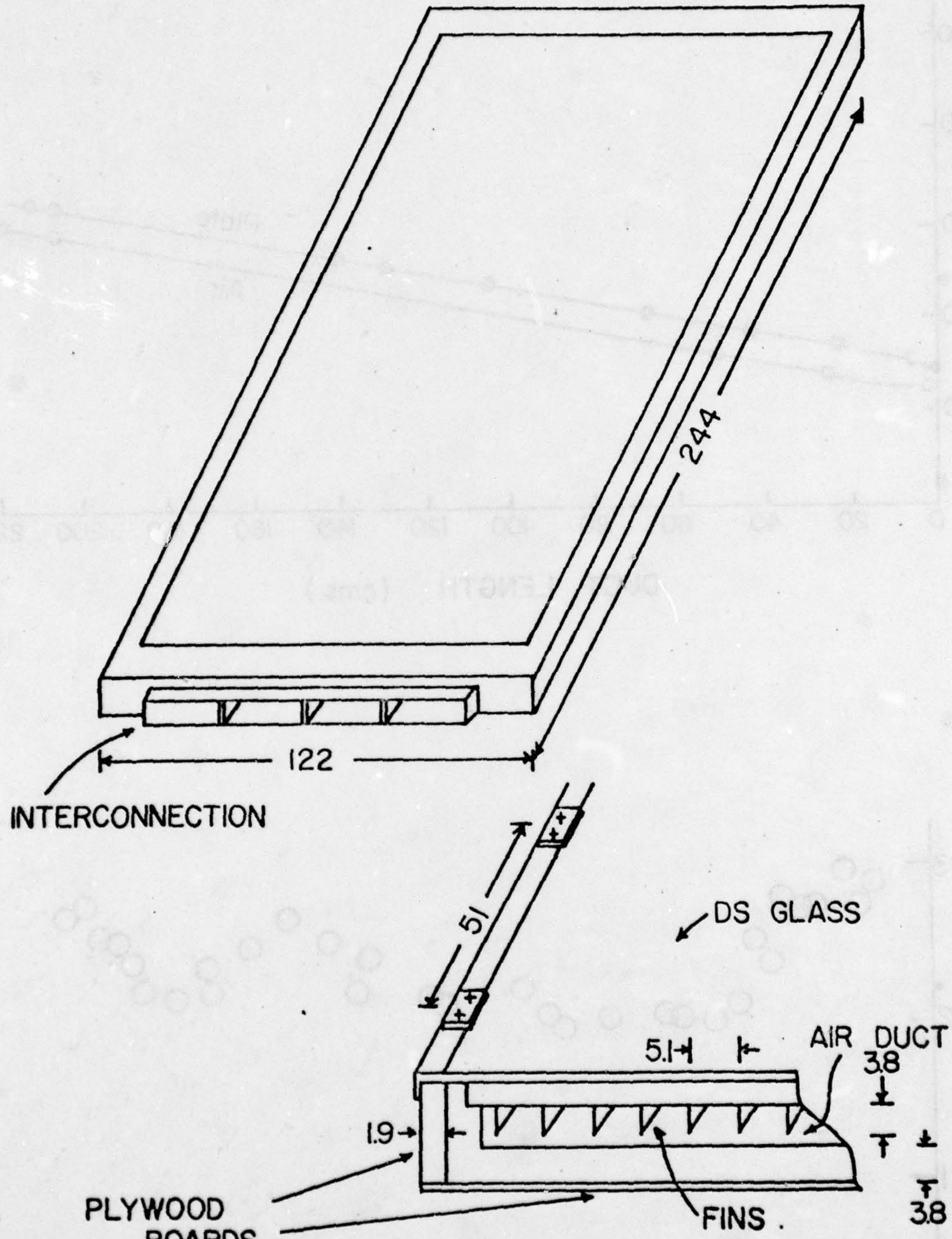
Fig. 1: Photograph of Solar One (from south-east).

Fig. 2: Schematics of a typical solar panel as deployed on Solar One.

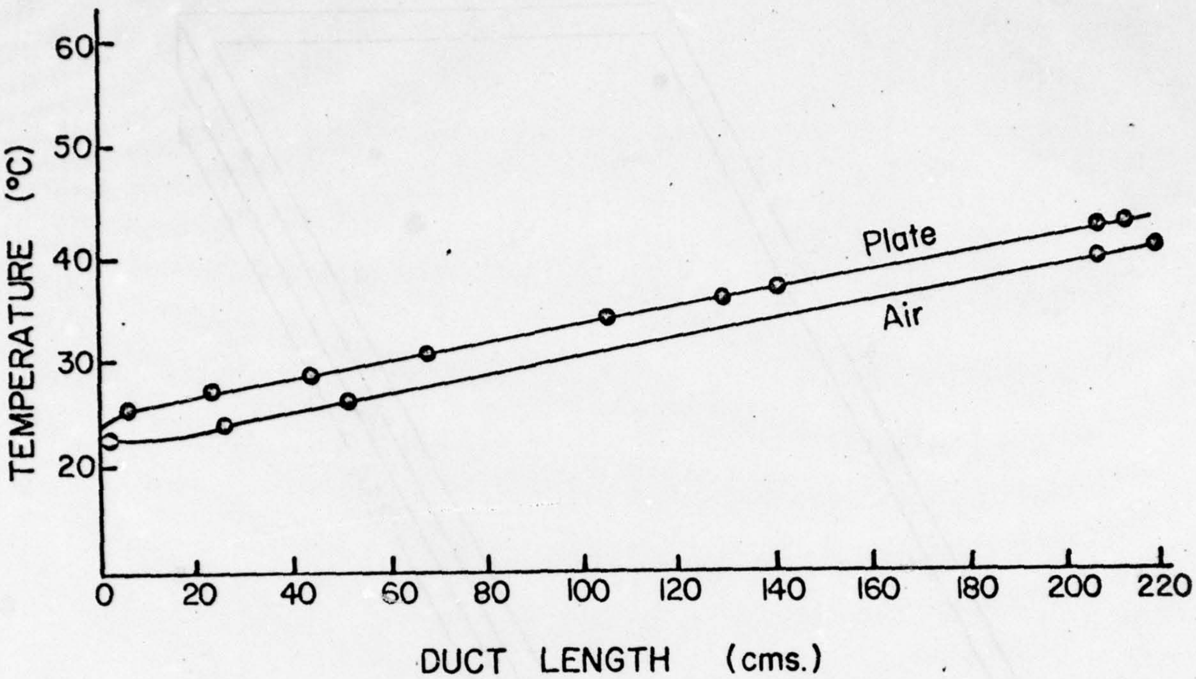
Fig. 3: Collector-plate and air temperature measured at the long axis of the collector.

Fig. 4: Measured efficiencies of sub-panel P1-2 (104 cells) as a function of deployment time on the roof of Solar One.





(all dimensions are in centimeters)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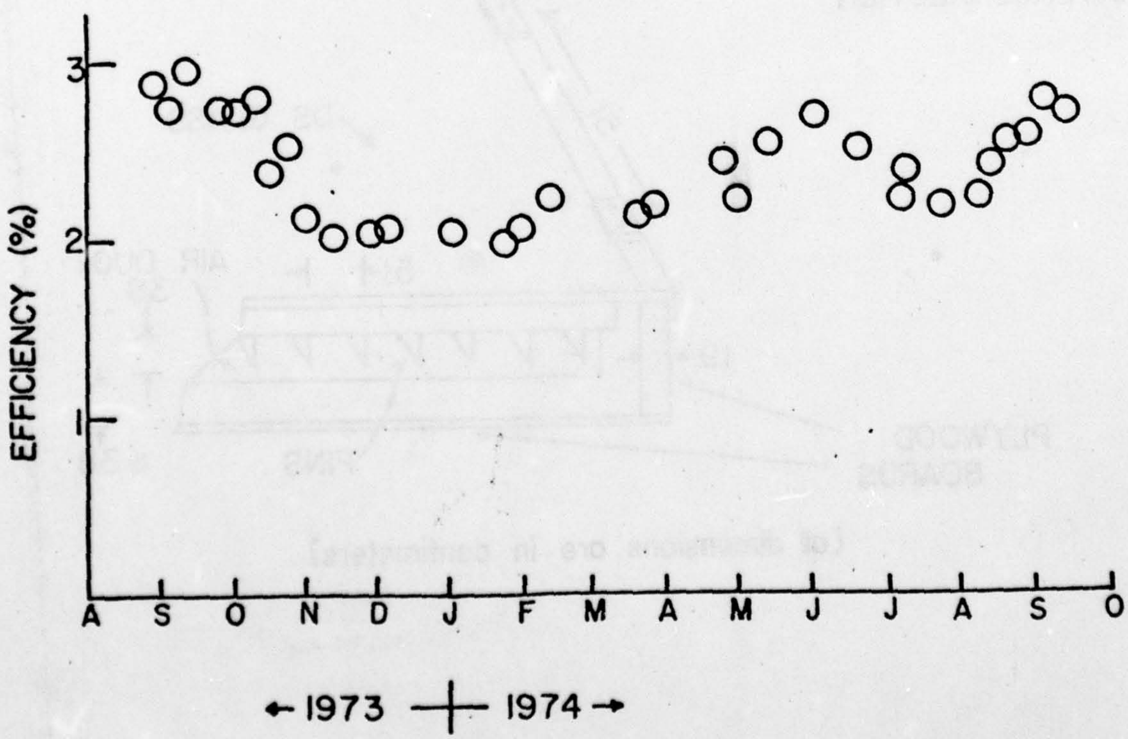
40
30
20
Plate
Air
0 20 40 60 80 100 120 140 160 180 200 220
DUCT LENGTH (cms.)


EFFICIENCY (%)
3
2
1
A S O N D J F M A M J J A S O
←1973 — 1974→